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Proceedings of the Workshop on High Altitude Data Assimilation and Modeling

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Proceedings of the Workshop on High Altitude Data Assimilation and Modeling

I: Overview

The Workshop on High Altitude Data Assimilation and Modeling was held 16-17 September 2014 at the Naval Research Laboratory (NRL) in Washington, DC. Its primary objective was to provide a forum where members of the research community could discuss recent advances in high-altitude atmospheric data assimilation (DA) and modeling related to both Department of Defense (DoD) and civilian efforts to support and improve operational numerical weather prediction (NWP). A secondary objective of the workshop was to give stakeholders in the high altitude DA/NWP enterprise the opportunity to discuss future research efforts, specifically motivated by the anticipated gap in operational stratospheric/mesospheric observational capabilities resulting from the end of the Defense Meteorological Satellite Program (DMSP).

The workshop was organized by John McCormack (*Space Science Division, NRL*). Fifteen attendees from NRL, NASA, NOAA, and Johns Hopkins University participated in the two-day workshop. The first day began with presentations describing the high-altitude DA/NWP programs at each participating institution. These were followed by individual invited presentations highlighting recent developments in the areas of instrumentation, assimilation, and modeling. The second day began with several presentations describing current progress and future directions in various aspects of high-altitude data assimilation and modeling research. Subsequent discussions among all participants focused on identifying particular high-altitude observational and modeling capabilities that are essential for continued progress in the field.

From these discussions, the following conclusions emerged reflecting the consensus opinion of the various participants:

- Extension of current DoD and civilian operational atmospheric prediction systems to higher altitudes requires continuous monitoring of meteorological state variables (e.g., temperature, pressure, constituents) in the 50-100 km region for forecast initialization and verification. High quality global observations of these variables from operational space-based platforms provide crucial information that is vital to sustain both current and future high-altitude DA/NWP capabilities.

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- The end of the DMSP program will lead to a “data gap” in global high-altitude observations that will degrade current stratospheric forecast capabilities used by several operational missions, e.g., the Broad-Area Maritime Surveillance System (BAMS) using unmanned aerial vehicles (UAVs) such as the Global Hawk. It will also hinder progress in the integration of upper atmospheric forecast capabilities into space weather prediction systems needed for Over the Horizon Radar (OTHR) applications.
- The nominal lifetime of existing operational DMSP platforms is 5 years. The time frame of this looming “data gap” is approximately 5-10 years, based on typical timelines for developing, building, and launching operational space-based observing platforms. Thus a suitable replacement systems could be considered sooner rather than later, in order to minimize any potential for a possible negative impact of this data gap on current and future high altitude DA/NWP capabilities. **At a minimum, continued global temperature sounding capability for the 50-100 km altitude region is needed.**
- Researchers could conduct targeted DA/modeling studies that clearly demonstrate (1) the utility of existing high-altitude observations in the 50-100 km region for current high altitude DA/NWP systems and (2) demonstrate how this “data gap” could possibly affect the performance of these and future systems.
- The results of these studies could provide useful information to stakeholders within NRL and at other DoD and civilian agencies, to include:
 - Chief of Naval Operations (OPNAV)
 - Naval Meteorology and Oceanography Command (CNMOC)
 - The Joint Center for Satellite Data Assimilation (JCSDA)
 - NOAA’s Space Weather Prediction Center (SWPC)
 - Air Force Weather Agency (AFWA)
 - NASA Goddard Space Flight Center (GSFC)

The workshop agenda and schedule is provided in Chart 1. Section II provides background information describing the motivation for this workshop. Section III provides descriptions of the programmatic overviews and invited presentations presented on Day 1 of the workshop. Section IV describes the contributed presentations given on Day 2. Section V provides a summary of the workshop discussions that ultimately led to the consensus conclusions listed above. Section VI lists the participants and their affiliations. Section VII provides a bibliography of relevant publications.

CHART 1. WORKSHOP AGENDA AND SCHEDULE

Tuesday 16 September 2014: Programmatic Overviews and Invited Presentations

0915-0930 Welcome and Introduction

0930-1000 Navy Global Coupled NWP/DA Systems Under ESPC (Melinda Peng, NRL)

1000-1030 Assimilation of SSU/AMSU Radiances in the NCEP/GFS (Craig Long, NCEP)

1045-1115 Recent Progress with NAVGEM I: Data Assimilation (Nancy Baker, NRL)

1115-1145 Recent Progress with NAVGEM II: Modeling (Tim Whitcomb, NRL)

1145-1200 Group Discussion (all participants)

1300-1330 Overview of Activities at the CCMC (Masha Kuznetsova, NASA GSFC)

1330-1400 Upper Atmospheric Data Assimilation (Alex Chartier, APL/JHU)

1400-1430 Ground-to-Space Modeling (Fabrizio Sassi, NRL)

1500-1530 Near-Space Meteorological Observations (John McCormack, NRL)

1530-1600 Group Discussion (all participants)

Wednesday 17 September 2014: Contributed Presentations and Breakout Sessions

0900-1000 Wind and Temperature Observations from the Ionospheric Connection Explorer (Chris Englert, NRL)

1000-1100 Infrasound and High-Altitude Data Assimilation (Doug Drob, NRL)

1100-1200 Breakout Session I: Discussion of Current and Future High Altitude Observations

1330-1430 Current Topics in High Altitude NWP/DA Research

1330-1400 Applications of Ensemble Forecasts in Middle Atmosphere Data Assimilation (Karl Hoppel, NRL)

1400-1430 High-Altitude Physical Parameterizations (John McCormack, NRL)

1430-1530 Breakout Session II: What is the Future of High-Altitude DA/NWP ?

1530-1600 Summary Discussion (all participants)

II: Background and Motivation

There is a concerted effort at both the national and international levels to extend operational NWP systems up to 100 km altitude. This is motivated in part by the need to increase forecast skill near the surface through improved assimilation of global satellite radiance observations. These types of observations are a vital source of information on atmospheric state variables (temperature, pressure, etc.) needed for forecast model initial conditions. This effort is also motivated in part by the increasing number of Navy and DoD operations that rely on accurate atmospheric analyses and forecasts in the 0-100 km altitude region, which include BAMS utilization of high-altitude UAVS such as Global Hawk, and development of new space weather prediction capabilities needed for OTHR applications.

One such effort that is particularly relevant to these activities is the national Earth System Prediction Capability (EPSC) initiative, which coordinates a broad multi-agency effort among the Navy, Air Force, NOAA, NASA, the Department of Energy, and the National Science Foundation. EPSC focuses on identifying and developing sources of extended range predictability from synoptic to intra-seasonal and inter-annual timescales with the future addition of a multiannual to multi-decadal capability [NRC, 2010]. The Navy Global Environmental Model (NAVGEN) is the Navy's current operational NWP system [Hogan *et al.*, 2014]. Designated as a bridge technology to a next-generation EPSC, NAVGEN development represents the Navy's long-term strategic commitment to EPSC goals.

Currently, the Special Sensor Microwave Imager/Sounder (SSMIS) on board DMSP satellites F16, F17, F18, and F19 includes upper atmosphere sounding (UAS) channels extending to ~110 km altitude. NRL researchers have recently developed a sophisticated new capability to assimilate these UAS radiances operationally into NAVGEN using a fast radiative transfer code containing new Zeeman physics, providing accurate atmospheric initial conditions up to ~85 km altitude [Swadley *et al.*, 2008 ; Hoppel *et al.*, 2013]. The last SSMIS instrument is anticipated to fly on DMSP F20, but the launch status of this platform is uncertain at this time. **Beyond that, there are no plans currently for any UAS channels on future operational defense or civilian sensors, presaging a large operational data void from 50-100 km that will significantly degrade the performance of future NWP systems.** In addition, NASA research satellites that have provided global high-altitude temperature and constituent observations over the past 5-10 years will soon reach the end of their mission lifetimes, and there are no plans in place to replace them.

The first coupled ground-to-space (0-100 km altitude) data assimilation and forecast system, the NOGAPS-ALPHA prototype, was developed at NRL from 2001-2011 [Eckermann *et al.*, 2009]. Several of the physics modules originally developed for NOGAPS-ALPHA have

already been successfully transitioned to FNMOC in order to improve the high-altitude forecast capabilities of NAVGEM. Taking advantage of NRL's current position as a leader in high-altitude data assimilation and predictability research, this workshop brought together interested parties to discuss the future of high altitude atmospheric data assimilation and modeling research as it relates both to the ongoing ESPC initiative and to other related Navy, DoD, and civilian efforts to enhance and improve operational NWP. It was specifically motivated by the anticipated gap in operational high altitude atmospheric prediction capabilities resulting from the upcoming end of the Defense Meteorological Satellite Program (DMSP). This gap could seriously degrade high altitude prediction capabilities just at the time when operational systems such as NAVGEM become capable of exploiting the full potential of these types of observations.

III. PROGRAMMATIC OVERVIEWS AND INVITED PRESENTATIONS

The Earth System Prediction Capability (ESPC)

Melinda Peng (*Marine Meteorology Division, NRL*)

The first workshop presentation described ESPC, a national, multi-agency collaborative effort to leverage resources to develop the next-generation Earth prediction system. ESPC facilitates transition of research to operations and supports shared needs while accommodating diverse agency requirements. A key goal of ESPC is to extend current Earth system prediction capability beyond the weather regime to sub-seasonal, seasonal, inter-annual, and decadal time frames. The ESPC road map plans for initial operational capability in 2018, with full operational capability by 2025. The presentation concluded with a list of items for group discussion: determining a new top model level required for extended predictions to 90 days and longer; determining optimal model vertical resolution; improved understanding and demonstration of how upper level phenomena impact low-level extended range predictions; and exploration of future data opportunities and assimilation strategies. During the question and answer period, possible development of an 80-level operational version of NAVGEM was discussed with a top near 0.01 hPa. Optimal model vertical grid spacing in the stratosphere for resolving features important for seasonal prediction such as the quasi-biennial oscillation (QBO) was suggested to be on the order of 0.5 km, which would necessitate running at lower horizontal resolution (possible T119) in order to avoid excessive computational overhead.

Preliminary Results from Assimilation of SSU & AMSU Radiances in the NCEP/GFS in Preparation for CFSv3

Craig Long (*Climate Prediction Center, NOAA*)

Preliminary test results from assimilation of Stratospheric Sounding Unit (SSU) and Advanced Microwave Sounding Unit (AMSU) radiances into the National Center for Environmental Prediction (NCEP) Global Forecast System (GFS) were presented. The tests were being conducted to address issues in the Climate Forecast System Reanalysis (CFSR) during the transition from the SSU to the AMSU radiances in October 1998. Issues with the CFSR associated to radiance assimilation in the stratosphere included breaking up the reanalysis into six streams, bias correction of SSU Channel 3, and not assimilating AMSU Channel 14. Other reanalyses handled this transition in different ways from switching immediately over from the SSU to AMSU in 1998 to assimilating both for an extended period of time. The greatest temperature impacts from this transition occurred above 10 hPa. The test runs showed that transitioning immediately from SSU to AMSU resulted in warmer temperatures above 2 hPa and cooler temperatures between 2-10 hPa. Assimilating both SSU and AMSU radiances reduced these temperature biases by a factor of two.

Assimilation in the Upper Stratosphere and Mesosphere: Role of radiances

Nancy Baker (*Marine Meteorology Division, NRL*)

This presentation outlined high-altitude data assimilation efforts for NWP applications at NRL's Marine Meteorology Division. The objective of this research is to improve the Navy's NWP skill from the surface to near-space by developing stratosphere and mesosphere assimilation capabilities for the Navy's new assimilation system, NAVDAS-AR. This is accomplished by extending the top of NAVDAS-AR to 90 km altitude and by adding middle atmosphere data from new operational and research satellite sensors such as SSMIS, SABER and MLS. The expected payoffs are new stratospheric and mesospheric wind & temperature analyses for middle atmosphere research, improved long-range weather forecasting capabilities, and new high-altitude forecasting capabilities for DoD systems.

Updates to the NAVGEM in the Stratosphere

Tim Whitcomb (*Marine Meteorology Division, NRL*)

Several recent advances in the NAVGEM forecast model were highlighted. A new formulation of the semi-Lagrangian dynamical core using perturbation virtual potential temperature (or $p\text{-}\theta$) has been introduced that improves numerical stability, which in turn reduces the need for numerical diffusion and semi-implicit decentering, and also allows for better-represented gravity waves. T359L50 NAVGEM forecast/assimilation tests with the $p\text{-}\theta$ formulation reduced background (model) bias and improved assimilation of SSMIS

channel 22 radiances. Introduction of a new non-orographic gravity wave drag parameterization further reduced the model bias in this case. The impact of a new water vapor photochemistry parameterization was also discussed. NAVGEM forecast model simulations showed that implementation of this photochemistry parameterization, combined with a quality control module to constrain model humidity values above the tropopause to realistic values, significantly improved the model longwave cooling calculations, leading to reduced model temperature biases in the extratropical lower stratosphere. These model improvements are slated for transition to operational NAVGEM in the near future, and will allow for better assimilation of higher-peaking satellite radiances such as SSMIS UAS. Future efforts will continue to focus on improvements in the stratosphere for longer-term prediction.

The Community Coordinated Modeling Center: Overview of Activities

Masha Kuznetsova (*Space Weather Research Center, NASA*)

The Community Coordinated Modeling Center (CCMC) was established in 2000 as an element of the National Space Weather Program, and is designed to be a flexible, long-term solution to the Research-to-Operations (R2O) transition problem. The specific goals of the CCMC are to: (1) facilitate research, development, and educational efforts in the scientific community; (2) address NASA space weather needs; and (3) support R2O transitions. Currently CCMC hosts over 60 different space weather models, to include empirical, physics-based, and assimilative models. Members of the research community can access model output through a web-based interactive Runs-on-Request service. Interactive on-line visualization and analysis capabilities are also available. CCMC currently partners with NOAA, NASA, and AFWA to support real-time space environment monitoring, event analysis, system science, and instrument validation.

Upper Atmospheric Data Assimilation

Alex Chartier (*Advanced Physics Lab, Johns Hopkins University*)

This presentation first provided a review of thermosphere/ionosphere physics and ionospheric forecasting theory, then described recent upper atmospheric data assimilation efforts at APL. The presentation emphasized that detailed knowledge on the composition of the thermosphere is crucial to understanding, and predicting, rapid changes in the state of the ionosphere. Observations from NRL's Special Sensor Ultraviolet Limb Imager (SSULI) and APL's Special Sensor Ultraviolet Spectrographic Imager (SSUIs) instruments on DMSP platforms are currently providing valuable information that are beginning to be assimilated as part of a forecast system.

Ground-to-Space Modeling

Fabrizio Sassi (*Space Science Division, NRL*)

A recent development in ground-to-space (G2S) modeling is to constrain the lower atmospheric meteorology in a state-of-the-art general circulation model (GCM) of the whole atmosphere. Using this approach, it is possible to study the response of the thermosphere-ionosphere system to meteorological variability near the surface for past events. Using an extended version of the Whole Atmosphere Community Climate Model (WACCMX) coupled to global synoptic meteorological analyses produced with NRL's NOGAPS-ALPHA system, the upper atmospheric response to a sudden stratospheric warming during January 2009 has been extensively studied. Output from these WACCMX simulations with specified dynamics (SD-WACCMX) has also been used to specify thermospheric boundary conditions for NRL's SAMI model of the thermosphere, producing a G2S analysis and forecast system capable of using information from operational high-altitude atmosphere observations such as SSMIS UAS. Preliminary results from this G2S system demonstrate that high-altitude atmospheric specifications are critical to understand the dynamical coupling between the thermosphere and the ionosphere. Future requirements to predict ionospheric behavior (both for civilian and military uses) will rely on accurate forecasts of the neutral atmosphere up to 100 km altitude, which will not be possible without assimilation of operational, space-based observations of atmospheric state variables (e.g., temperature, density, etc.) in the 50-100 km region.

Near-Space Meteorological Observations

John McCormack (*Space Science Division, NRL*)

Forecast models require accurate atmospheric initial conditions from operational measurements to produce skillful predictions. SSMIS currently provides the only source of operational data from 50-100 km altitude for assimilation into these new high-altitude NWP systems. To that end, NRL scientists recently completed and published a demonstration study in which thermal radiances from SSMIS UAS channels were assimilated into the Navy Global Environmental Model (NAVGEN) using new fast radiance assimilation codes that account for Zeeman line splitting by geomagnetic fields and Doppler shifts due to spacecraft motion [Hoppel *et al.* 2013]. The study revealed major error reductions in NAVGEN analyses and forecasts from ~30-100 km altitude when assimilating operational SSMIS UAS radiances from DMSP F16, F17 and F18. This capability is currently undergoing pre-operational testing and is expected to transition to operations at FNMOOC this year. The capability to assimilate and forecast operationally from 0-100 km is an essential first step towards future whole-atmosphere systems extending to ~300 km altitude or more that can predict space weather in addition to atmospheric and near-space weather.

IV. CONTRIBUTED PRESENTATIONS

Wind and Temperature Observations from the Ionospheric Connection Explorer

Chris Englert (*Space Science Division, NRL*)

The Ionospheric Connection Explorer (ICON) mission will explore the space environment near Earth to identify the various sources of variability both from below (i.e., atmospheric variability) and from the sun through interaction of the solar wind with the magnetosphere. A key component of ICON is the Michelson Interferometer for Global High-resolution Thermospheric Imaging (MIGHTI), which will measure velocity and direction of thermospheric winds by observing Doppler shifts of naturally occurring airglow lines using Doppler Asymmetric Spatial Heterodyne (DASH) interferometers. The MIGHTI instrument will also perform temperature measurements using multi-spectral measurements of the oxygen A-band shape. Together, the wind and temperature information from MIGHTI will provide an unprecedented view of the thermosphere/ionosphere system that can be used to validate NRL's emerging ground-to-space forecasting capabilities.

Infrasound and High-Altitude Data Assimilation

Doug Drob (*Space Science Division, NRL*)

Infrasound refers to sub-audible acoustic waves in the 0.1 to 20 Hz frequency range that can propagate through the atmosphere for hundreds of kilometers without significant attenuation. There are any natural sources (e.g., bolides, seismic activity, tsunamis) as well as man-made sources (e.g., high-yield conventional explosives, underground nuclear testing). High-altitude data assimilation is relevant for infrasound detection because the infrasound wave dispersion relation is strongly dependent on the background wind conditions throughout the depth of the entire atmosphere. Both research and operational infrasound communities already make use of upper atmospheric data assimilation products to varying degrees. Any degradation in the availability of operational high-altitude atmospheric observations will result in increased uncertainties of infrasound event detection, location, and characterization. In the future, infrasound observations may be inverted to validate upper atmospheric data assimilation products, and theoretically could even be used as an additional independent data source in future upper atmospheric data assimilation systems.

Applications of Ensemble Forecasts in Middle Atmosphere Data Assimilation

Karl Hoppel (*Remote Sensing Division, NRL*)

This presentation described methods for replacing static background error covariance estimates in the NRL Atmospheric Variational Data Assimilation System with Advanced

Representer (NAVDAS-AR) with estimates obtained using an ensemble approach. The background error covariance is an important element in data assimilation, as it controls the weighting of the background covariances, controls the spread of observation influence, and provides balance relationships through inter-variable correlations. Developing accurate background covariance error estimates for high altitudes is challenging for several reasons. First, there is a high amount of wave energy over all spatial scales - and with shorter time scales - than in the lower atmosphere. In addition, temperature-wind correlations in the 50-100 km region are different than in the troposphere, and the spatial correlations between different sets of observations at high altitudes are not currently well understood. Rather than replicating methods originally developed for NWP near the surface, next generation high-altitude NWP/DA systems must reformulate their approaches to estimating background error covariance to reflect the different geophysical processes at work in the upper atmosphere.

High-Altitude Physical Parameterizations

John McCormack (*Space Science Division, NRL*)

A prototype high-altitude numerical weather prediction (NWP) and data assimilation (DA) system has recently been developed based on the operational Navy Global Environmental Model (NAVGEN) that can generate global synoptic meteorological analyses every 6 hours from the ground to the lower thermosphere (~100 km altitude). In addition to assimilating operational meteorological observations in the 0-50 km altitude range, this high-altitude version of NAVGEN can also assimilate temperature and constituent measurements throughout the stratosphere and mesosphere obtained from satellite-based instruments, including the SSMIS UAS channels. This presentation discussed changes in the forecast model introduced to improve model accuracy and thus minimize bias at high altitudes. Results from this new system show how it can be used to (1) provide improved initial conditions for stratosphere-resolving NWP and climate models; and (2) investigate dynamical coupling between the troposphere, stratosphere, and mesosphere. A challenge facing high-altitude NWP efforts is the scarcity of operational satellite observations above 50 km. The importance of maintaining these types of observations for future development of unified ground-to-space forecast systems was discussed.

V. SUMMARY OF GROUP DISCUSSIONS

This section contains synopses of extensive group discussions held on both days of the workshop. These discussions produced the consensus conclusions listed in Section I.

Day 1 Group Discussion

Following the programmatic overviews and invited presentations, the discussion began by asking a fundamental question: Are operational global upper atmospheric observations such as those currently provided by SSMIS UAS channels needed for current and future Navy NWP/DA activities? The consensus response among the various participants was that these types of observations are in fact crucial not only for maintaining current capabilities but for meeting future anticipated Navy needs. In particular, the success of proposed ESPC and other Navy-relevant initiatives to develop seamless ground-to-space models could rely heavily on the availability of these types of observations. Attempts to “engineer around” the high-altitude data gap by, e.g., tuning parameters in a forecast model to produce a realistic upper atmospheric climate, would be unlikely to provide the same kind of accurate real time information on the day-to-day variations in atmospheric conditions that are currently available from the SSMIS UAS.

The next question posed was what members of the high altitude atmospheric DA and modeling community could do, both as individuals and as a group, to address the looming data gap on upper atmospheric observations posed by the end of the DMSP program? First it was noted that raising awareness of the issue within the broader scientific and managerial communities would be helpful, possibly through writing an article for submission to EOS or a similar publication. Next it was suggested that entraining other researchers in related fields (e.g., thermosphere/ionosphere modeling research community and operational space weather centers) could be valuable. The point was made that some effort should be made to change perception of these types of observations from “nice to have” to “need to have”. It was also noted that there is also a need to change the perception that there are currently a large number of operational microwave sensors in use, so if one (i.e., SSMIS UAS) goes away, there are enough other types of sensors to make up for the loss. To help change these perceptions, workshop participants suggested that more detailed studies describing the benefits of the unique high altitude capabilities of the SSMIS UAS channels could be carried out

The discussion then turned to a more pragmatic topic of how to address the high altitude data gap issue within the operational community. It was noted that explaining the problem in terms that are likely to be met favorably with program managers, e.g., cost benefit analysis assignment of realistic dollar values to any proposed solutions, would be a good first step. The Joint Requirements Oversight Council (JROC) was cited as an example of the process that any proposed strategies would have to work through. Finally, the idea of developing a micro-satellite approach as an alternative to a larger and more costly dedicated satellite program was put forward.

Day 2 Breakout Sessions

Current and Future High Altitude Observations

The discussion began by noting that just as the SSMIS UAS radiance assimilation in NAVGEM is nearing full operational capability, DMSP systems could reach mission end (either at F19 or F20), with no planned follow-on capability. When the SSMIS mission on DMSP ends, operational NWP systems will be faced with a data void at these altitudes, with large decreases in near-space prediction skill and related capabilities as a likely result. A question was raised asking if there have been any studies to date that have tried to quantify these decreases in skill. There was broad agreement that these types of studies are urgently needed.

Regarding future missions, it was noted that UAS channels were originally planned as part of CMIS (Conical scanning Microwave Imager and Sounder) on future Defense Weather Satellite System (DWSS) satellites. Such a capability would have leveraged current microwave assimilation capabilities developed for SSMIS that will transition to FNMOC as part of NAVGEM (Hoppel et al. 2013). Following the cancellation of DWS, the DoD re-assessed meteorological satellite (MetSat) requirements through the Space-Based Environmental Monitoring Analysis of Alternatives (AoA). Because of the availability of lower atmosphere sounding channels on US civilian and European satellites, there was speculation amongst the participants that perhaps replacing SSMIS sounding was not considered a priority for the next generation DoD weather satellite system, the so-called Weather Satellite Follow-on (WSF). It was also suggested that maintaining UAS channels were not specifically considered, possibly because their capabilities and value have only emerged recently. To the group's knowledge, no high-altitude sounding instruments in general and UAS in particular are not planned for WSF.

Based on these considerations, it was suggested that additional options might also need to be considered, such as spaceflight instruments on dedicated microsatellites or as hosted payload rideshares. Also mentioned were newer advanced sounding technologies, such as a fully digital microwave upper atmosphere sounding spectrometer (UASS), which has already shown significant promise for future UAS sounding. Finally, it was noted that industry is continuing to pursue development of fully digital microwave radiometer technologies. The consensus opinion was that such advances in technology could be kept in mind for any possible follow-on high altitude observational platform.

What is the Future of High-Altitude DA/NWP?

To begin the discussion, it was noted that major US operational NWP systems are now extending their altitude range up through the stratosphere and mesosphere and into the lower thermosphere. The looming operational data void between 50-100 km resulting from the end of DMSP poses a significant threat to both current and future operational Navy, DoD, and civilian NWP systems. Given the long lead time involved in developing, building, and launching new space-based observational platforms, there was agreement among the participants that serious attention needs to be paid to this issue now, so that any adverse effects can be mitigated in time.

Several strategies were proposed in order to raise awareness and gain support for continued high-altitude global observations. First, continued studies that demonstrate the importance of these observations in stratosphere-resolving NWP/DA systems and their contribution to improved NWP skill [e.g., *Gerber et al., 2010; Tripathi et al., 2014*] are in order. The traditional way to demonstrate impacts of existing instruments on NWP skill is through observational system experiments (OSE) using data denial methods. Second, the need for additional research was highlighted regarding the importance of these types observations for upper atmosphere models used to forecast space weather impacts on e.g., GPS, radio communications, OTHR, etc.).

In light of the ESPC initiative and other similar national and international efforts to unify models and move toward a seamless whole atmosphere model analysis and prediction capability, it was suggested that there is also a need invest in new and innovative studies showing the importance of middle/upper atmospheric observations to the performance of whole atmosphere models that forecast not just tropospheric weather over the 50-10 day range, but also generate predictions up through the thermosphere and over longer time scales (i.e., seasonal to decadal). It was suggested that observational system simulation experiments (OSSEs) could be conducted to help identify exactly what types of radiometric observations of the middle atmosphere are most needed in order to meet stated ESPC goals. It was agreed that the knowledge gained from these types of studies would be of great benefit to the NWP community in general, and would be of particular value to NRL's existing Navy, DoD, and civilian customers.

In closing, the workshop participants collaborated to produce a set of consensus conclusions regarding the current challenges facing the high altitude atmospheric data assimilation and modeling community. The consensus conclusions are listed in Section I.

VI. WORKSHOP PARTICIPANTS

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